Plasma Source Modelling for Future Lithography at 6.7 nm and Other Applications

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2011 International Workshop on EUV and Soft X-Ray Sources, Dublin, Nov.7th -10th . 2011

Outline

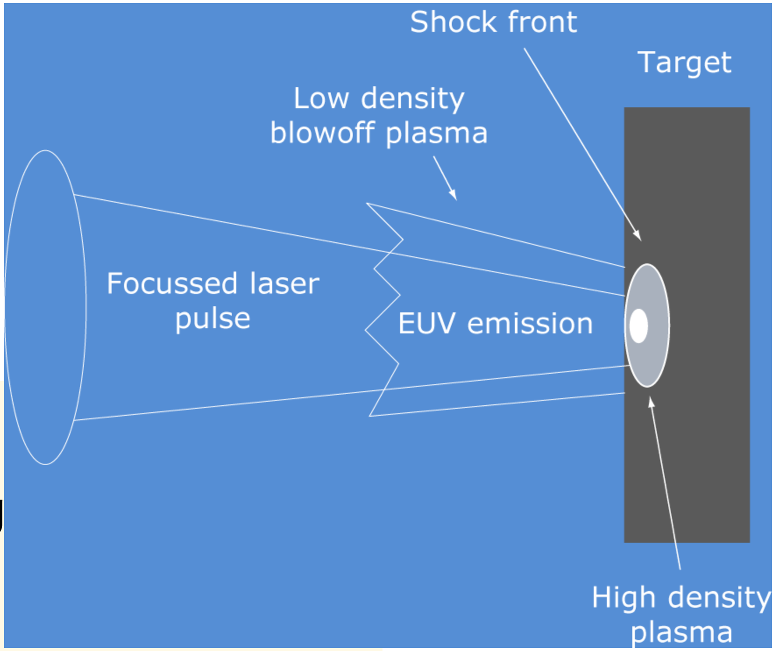
- Early work on spectroscopy of laser produced plasmas
- Theoretical results for plasmas @ 6.x nm
- Recent experimental results, parallels to Sn
- Other Directions

Laser produced plasma properties

Temperature depends on laser power density (Φ).

$T_e(\mathrm{eV}) \approx (\lambda^2\Phi)^{3/5}$

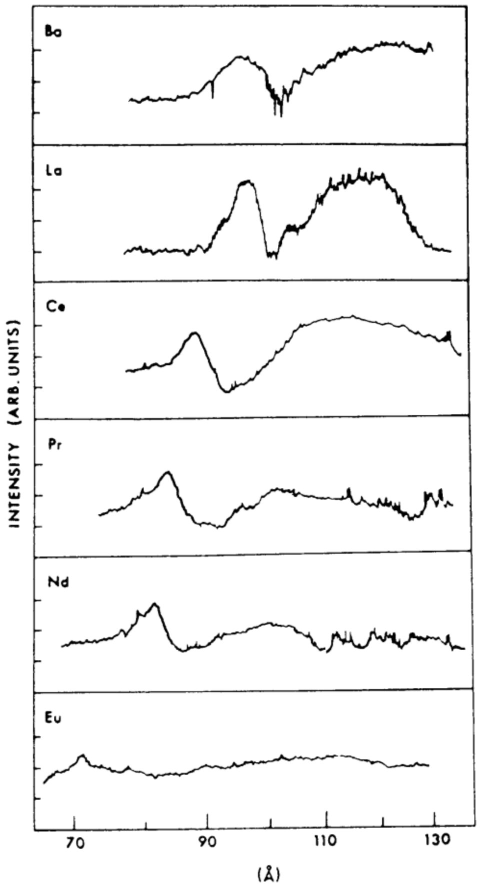
Average charge $\approx 0.67\,(AT_e)^{1/3}$



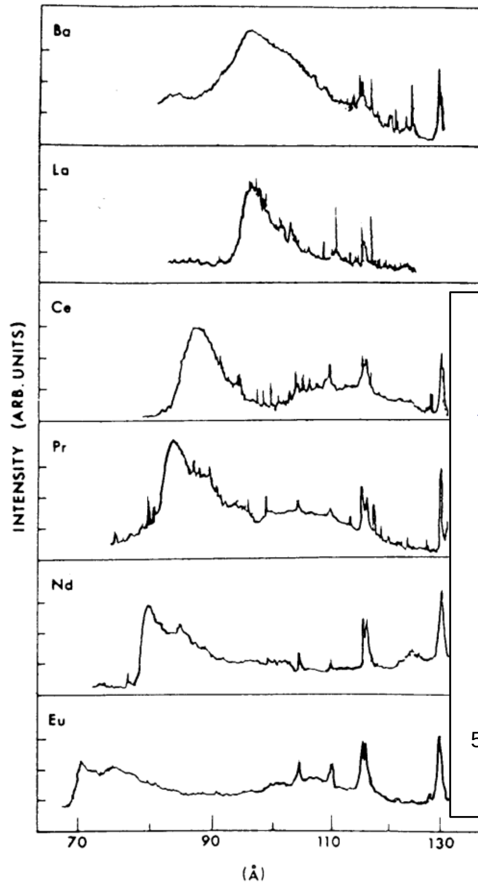
- Electron density $10^{19} - 10^{21}$ cm^{-3} depending on laser wavelength ($n_{ec} \sim 10^{21}/\lambda^2$ cm^{-3})
- Hottest at centre, cooler margins- opacity issues
- $\approx 100\ \mu$m size
- Expansion velocity $\approx 10^6 - 10^7$ cms^{-1} Fast ions and neutrals are a problem *(studied by e.g. Harilai et al JAP **98**, 013306, 2005, Mathew et al JPD **40**, 447, 2007, Fujioka et al JAP 2008)*

Spectra from plasmas of elements with Z > 50

Spectra from elements with Z > 50 contain lines and an intense UTA due to 4p – 4d and 4d-4f transition in ions with an outermost $4d^n$ ($1 \leq n \leq 9$)subshell.

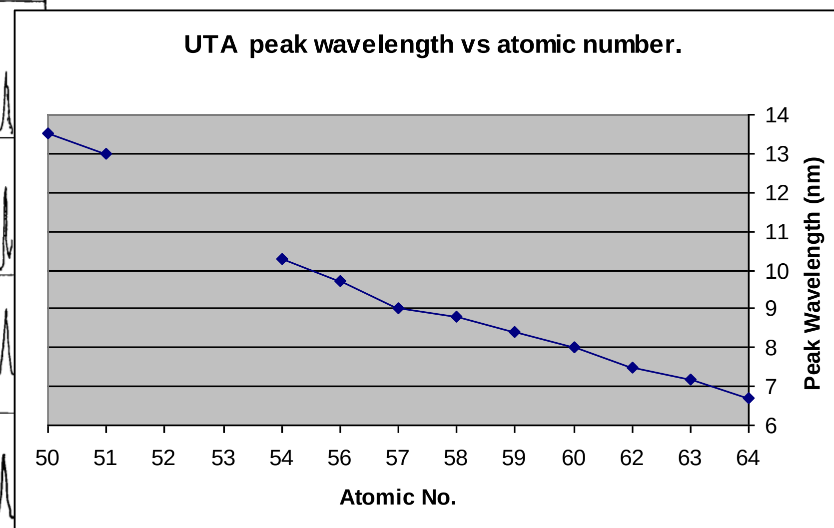


Metal Targets



Salt Targets

(Carroll and O'Sullivan PRA25, 275 1982)



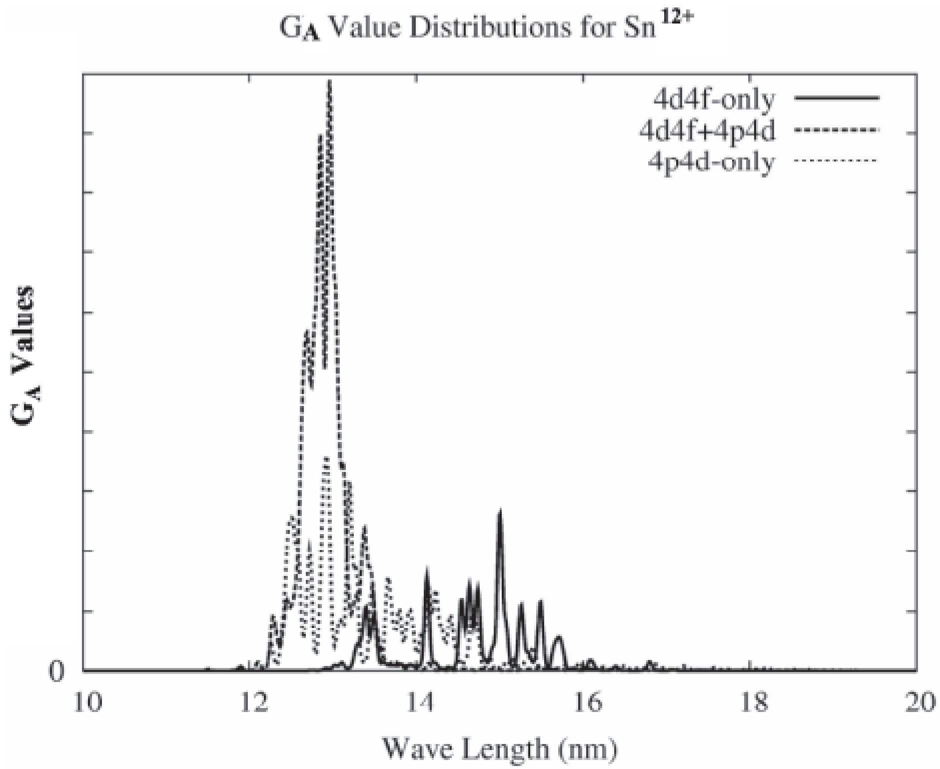
Differences are due to opacity

Configuration Interaction (CI) Effects

In spectra due to $4p^6 4d^n$-$4p^6 4d^{n-1} 4f + 4p^5 4d^{n+1}$ transitions

Configuration interaction causes

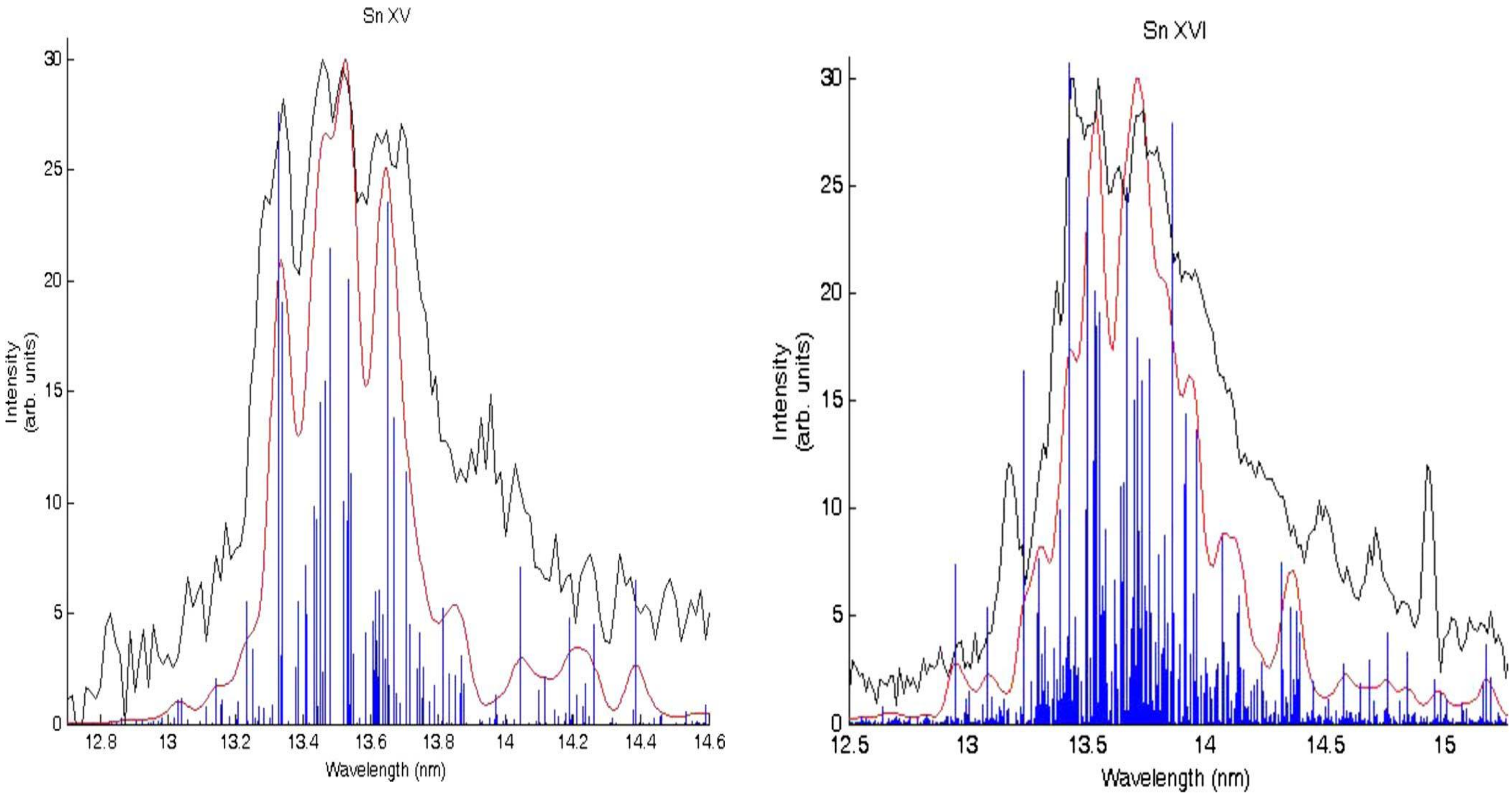
- Spectral narrowing.
- Strong peaking of oscillator strength.
- Localisation of transitions at approximately the same position in successive ion stages



F. Koike et al. J. Plasma Fusion Res. SERIES 7,253 (2006)

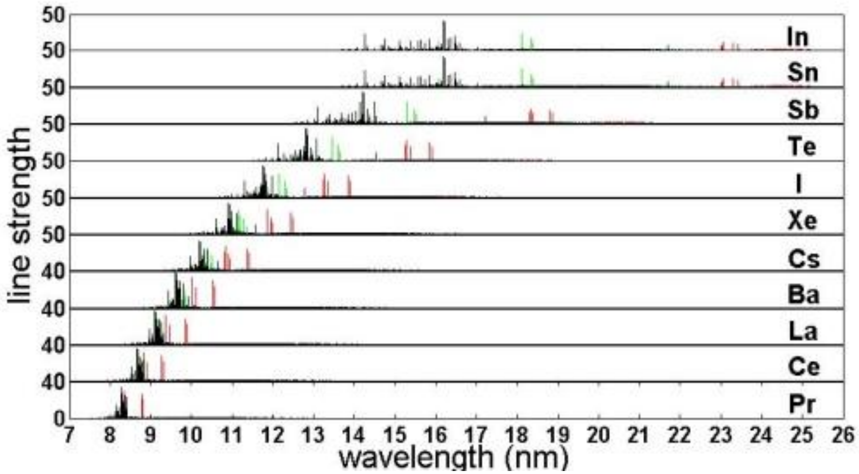
Satellite emission important at high densities

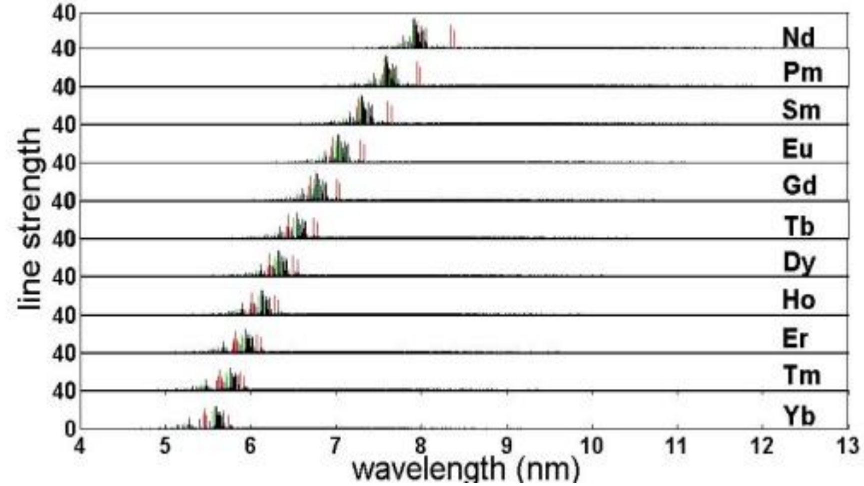
D'Arcy et al PRA 79, 042509 (2009)



In Charge Exchange Spectroscopy expect to see:
$4p^6\ ^1S_0 – 4p^54d\ ^1P_1$ of Sn XV,
instead observed $4p^54d – 4p^44d^2+4p^54f$ satellite lines.
Satellites lie on long wavelength side.

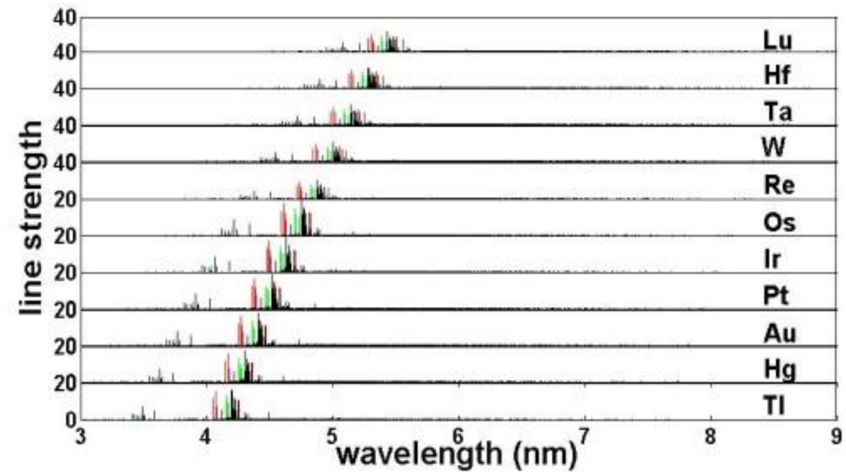
Variation of UTA position with Z





Width of UTA is a minimum in heavier rare earths, due to complete contraction of 4f wavefunction and almost constant value of <4d|4f> .

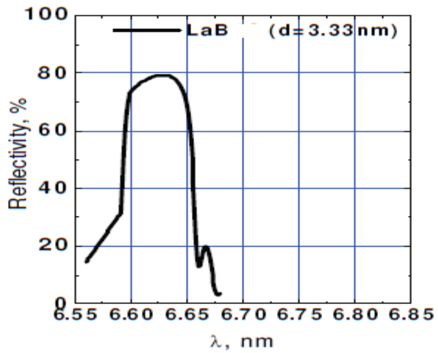
Broadens in very high Z due to 4d and 4p spin orbit splitting.



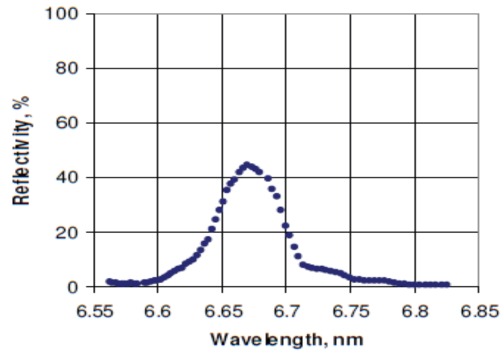
New Mirrors at 6.x nm

1st Pilot MLM coating La/B_4C for the range 6.6-7.0 nm

Theoretical



1st experimental MLM



λ=6.63nm, $\delta\lambda$=0.06nm, R=80% **λ=6.67nm, R=44.3%, $\delta\lambda$=0.06nm**

Reason for low R: interlayer diffusion → Reflectivity can be improved

Bandwidth of the optical column (11 mirrors):
$\Delta\lambda\Sigma/\lambda$(La/B4C)=0.6% (vs 2% for 13.5 nm)

IPM PhysTeX Slide 15 | Public ASML

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Shorter wavelength sources

IOP Publishing — Physica Scripta

Phys. Scr. 80 (2009) 045303 (6pp) — doi:10.1088/0031-8949/80/04/045303

EUV spectra of Gd and Tb ions excited in laser-produced and vacuum spark plasmas

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Interest in sources at 6.7 nm due to availability of Mo/B4C multilayer mirrors with a reflectivity of 40%

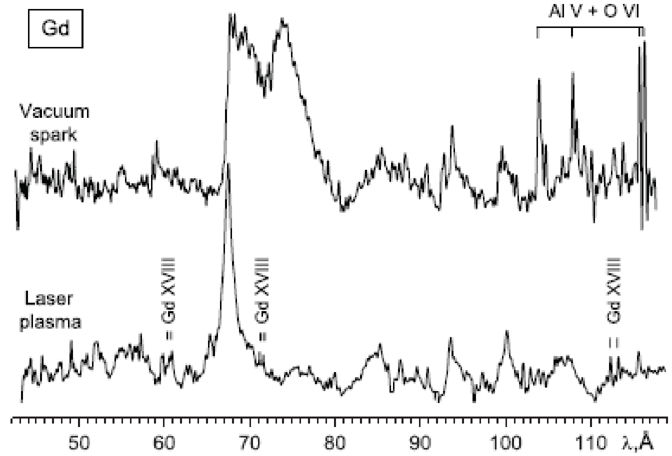


Figure 1. Spectra of gadolinium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace).

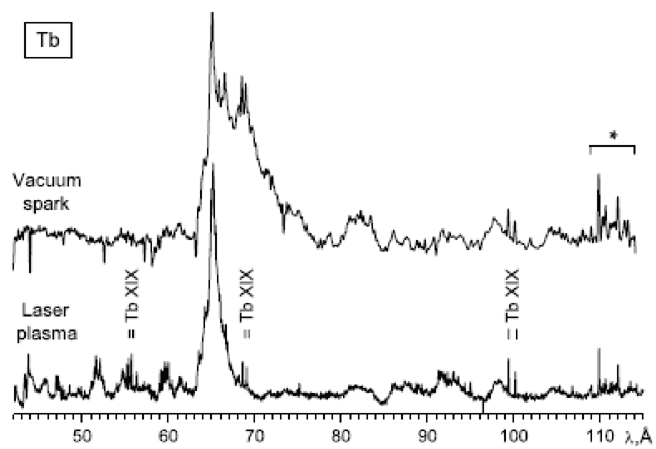


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

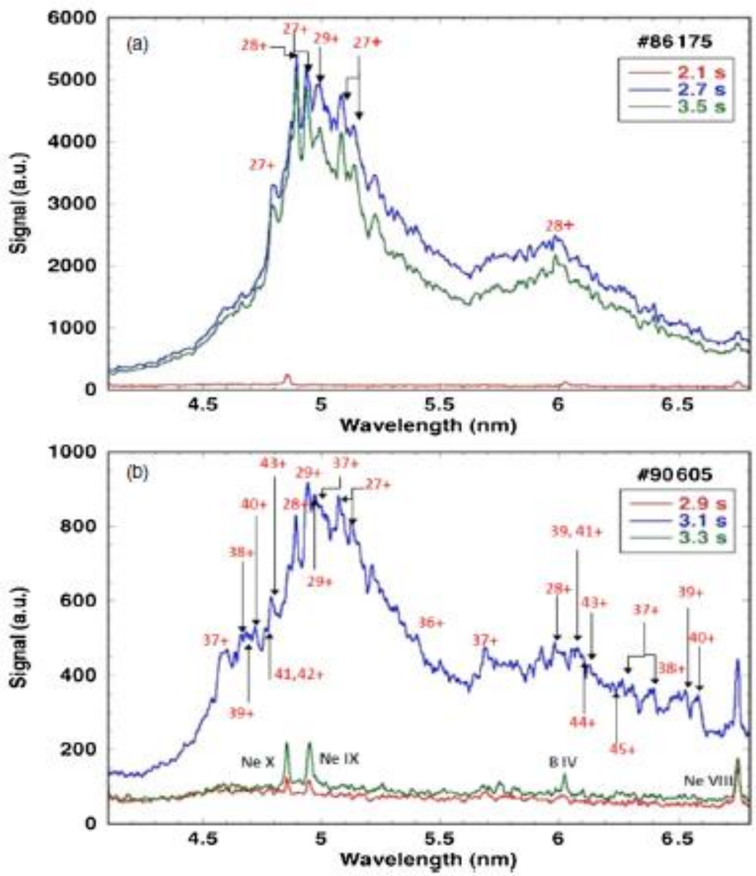
Most Important Stages?

IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 205004 (14pp) — doi:10.1088/0953-4075/43/20/205004

Tungsten spectra recorded at the LHD and comparison with calculations

C S Harte[1], C Suzuki[2], T Kato[2], H A Sakaue[2], D Kato[2], K Sato[2], N Tamura[2], S Sudo[2], R D'Arcy[1], E Sokell[1], J White[1] and G O'Sullivan[1]

[1] University College Dublin, Belfield, Dublin 4, Ireland
[2] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

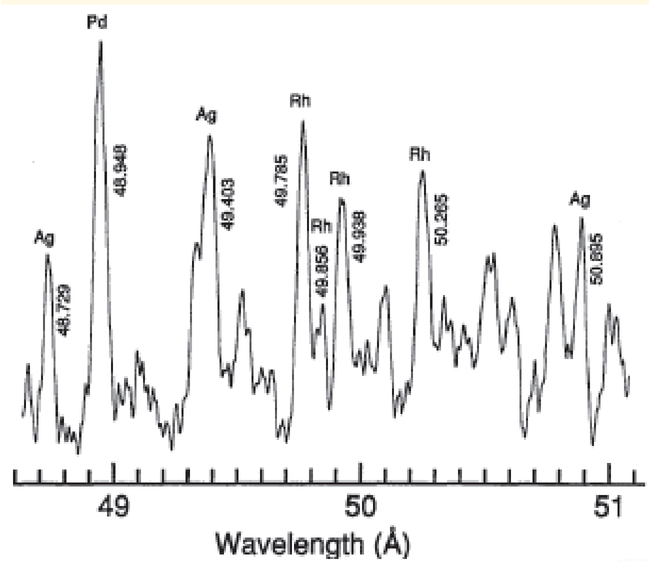


The most important transitions can be inferred from studies of W spectra.

They occur in Ag-like, Pd-like and Rh- like W^{27+}- W^{30+}. *Sugar et al JOSA 10, 1321 (1993)*

Gd XVIII-XX, Tb XIX - XXI

i.e. Ions with $4d^{10}4f$, $4d^{10}$ and $4d^9$ ground states



Ag–like and Pd–like lines

Laser:
3 J in 20 ns
$\lambda = 1.06\ \mu m$
$\Phi = (5\text{–}8)\times 10^{11}\ \mathrm{W cm^{-2}}$

Physica Scripta. Vol 26, 419–421, 1982

Resonance Lines in the Pd I Isoelectronic Sequence: I VIII to Ho XXII

J. Sugar and V. Kaufman

Physica Scripta. Vol. 24, 742–746, 1981.

Ag I Isoelectronic Sequence: Wavelengths and Energy Levels for Ce XII through Ho XXI and for W XXVIII

J. Sugar and V. Kaufman

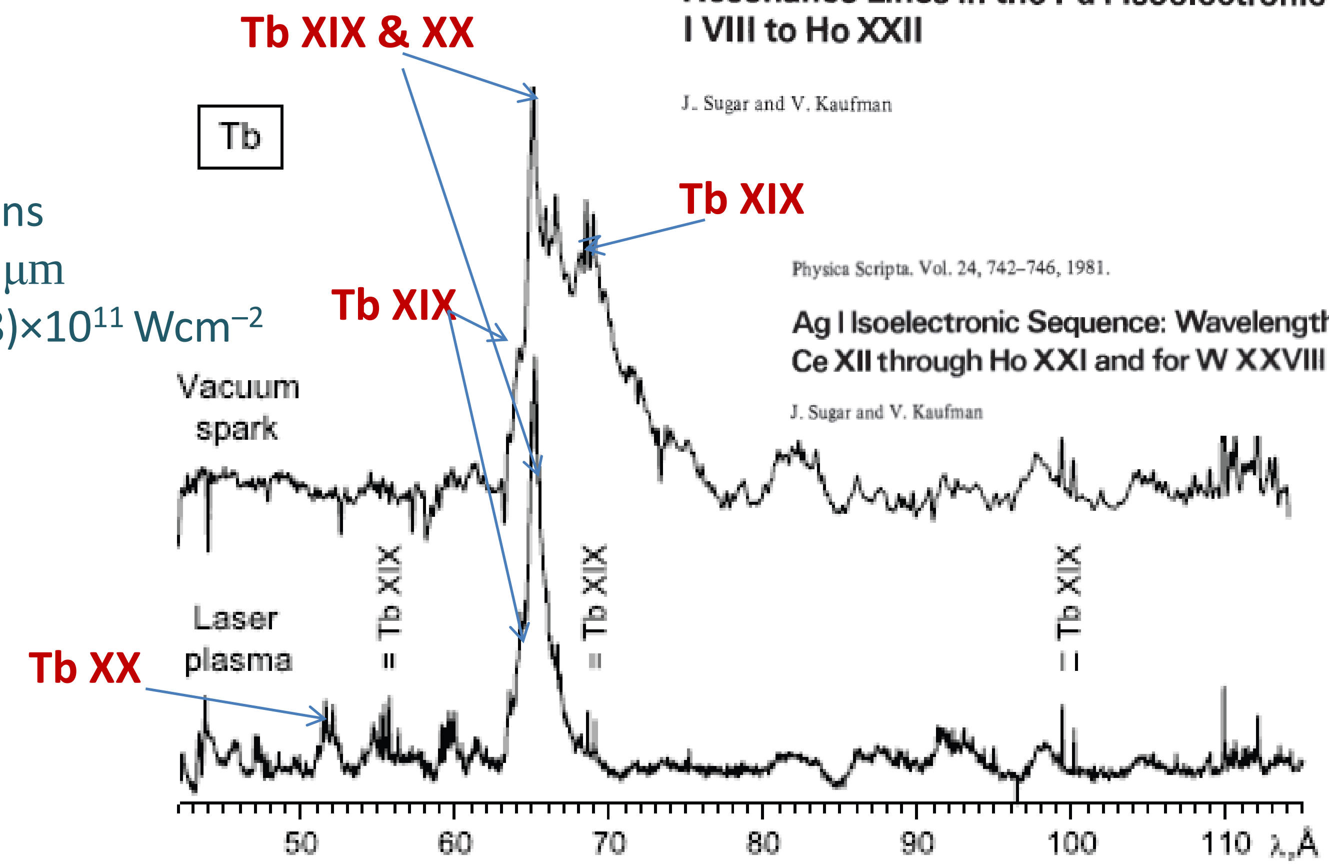
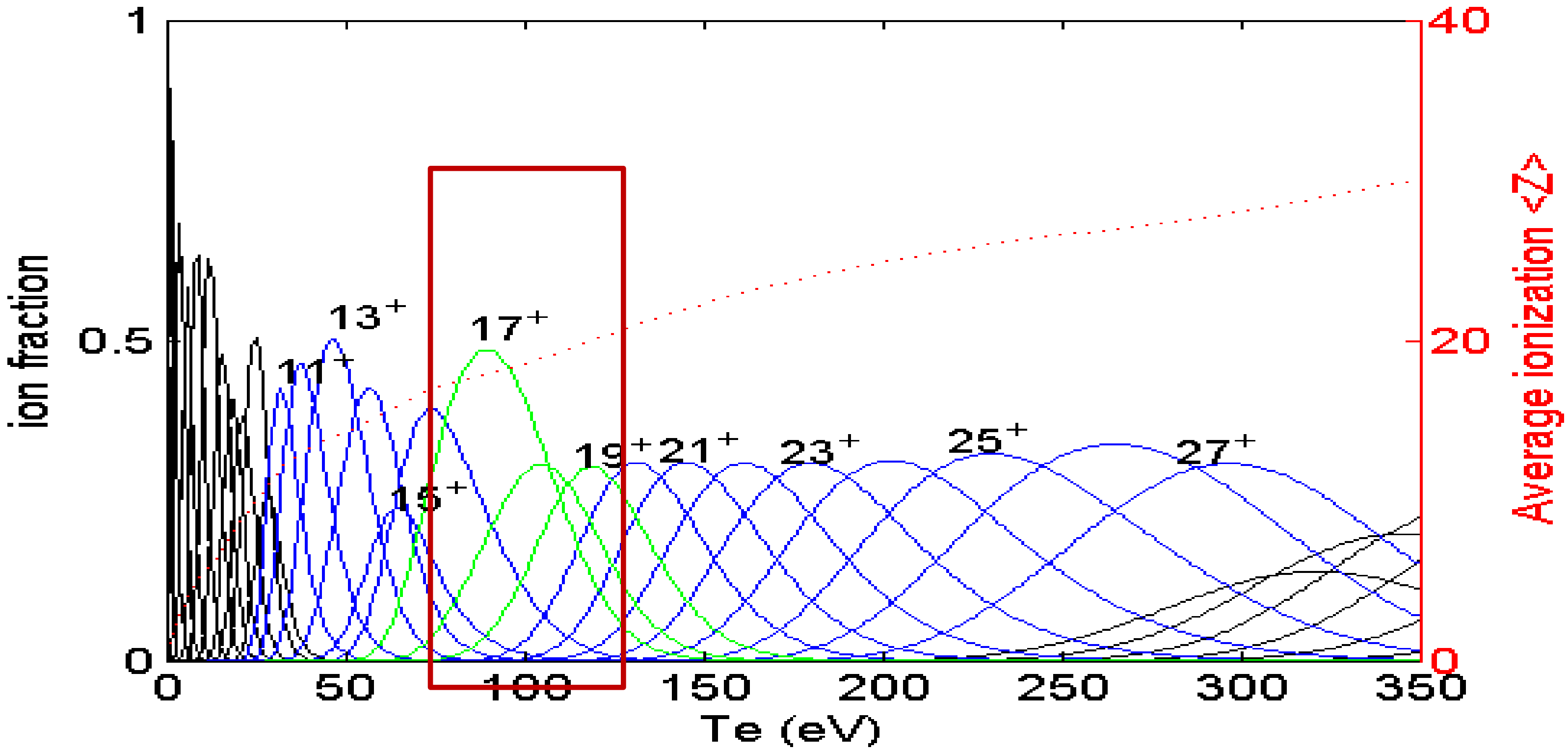


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). *, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

Power Density Requirements

Ion populations and average ionization of a Gd plasma as a function of T_e computed with the Collisional Radiative (CR) model. Most important stages are Ag-, Pd- and Rh- like (17+ - 19+)



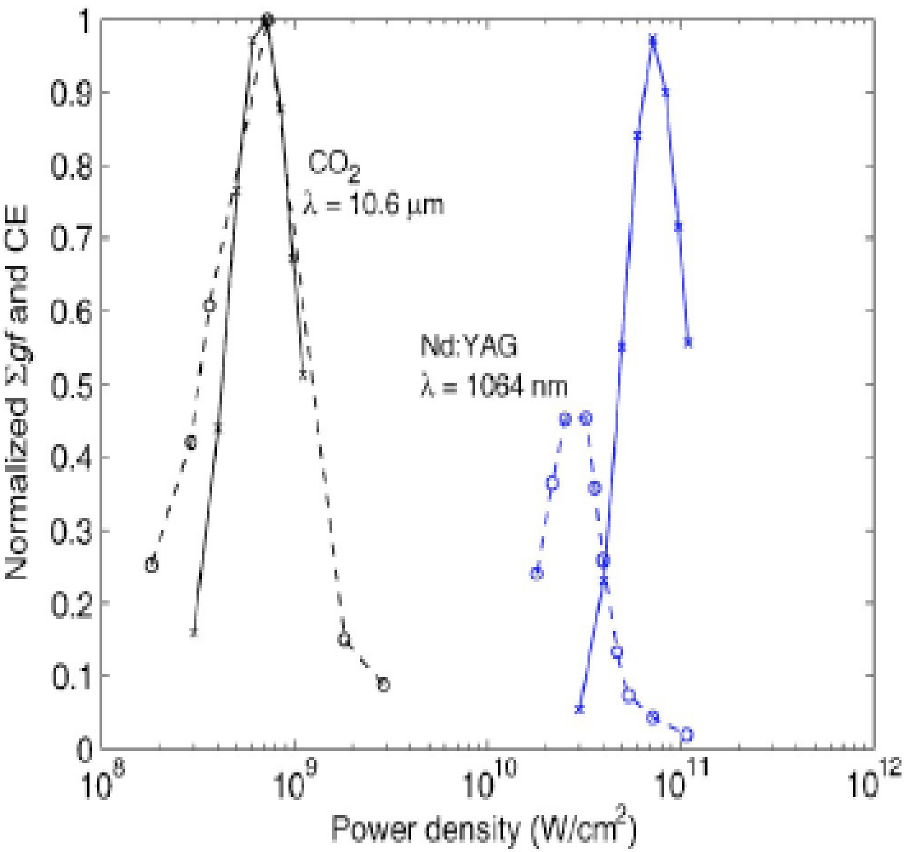
The laser power density required lies in the range

$2\times10^{12} – 10^{13}$ Wcm^{-2} @λ =1.06 µm

$2\times10^{11} – 10^{12}$ Wcm^{-2} @λ =10.6 µm

CO_2 vs Nd:YAG for drive laser

1-D Hydro modeling – demonstrated increase in CE for CO_2



- Lower power density required
- Less energy, better CE
- Improved opacity

$n_{ec} \approx 10^{21}\lambda^{-2}$ (cm^{-3})

1064 nm: $n_{ec} \approx 1\text{x}10^{21}$ cm^{-3}
10600 nm: $n_{ec} \approx 1\text{x}10^{19}$ cm^{-3}

J. White et al, *Appl. Phys. Lett.*, **90**, 181502 (2007)

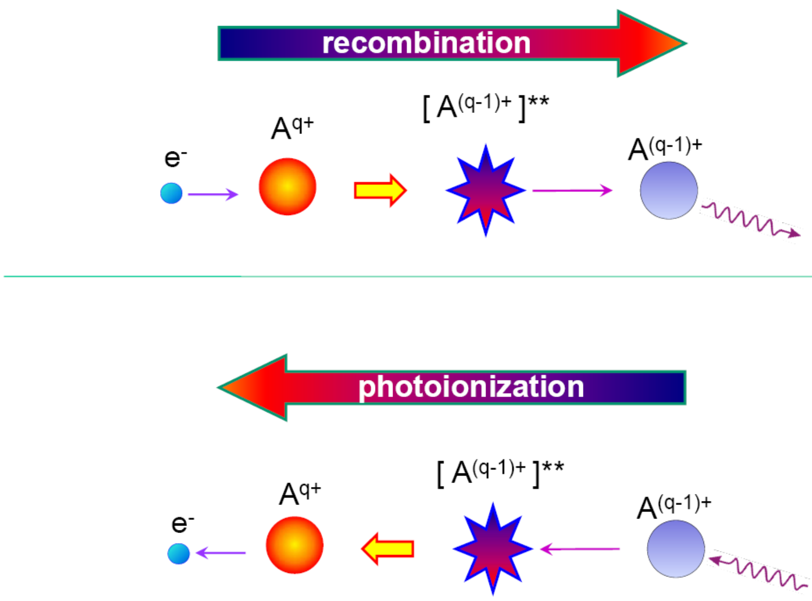
Gd ion fractions from a collisional-radiative model *(D. Colombant and G. F. Tonon, (1973) J. Appl. Phys. 44 3524)*

$$f_z = \frac{n_{z+1}}{n_z} = \frac{S(z)}{\alpha_r(z+1) + n_e \alpha_{3b}(z+1)}$$

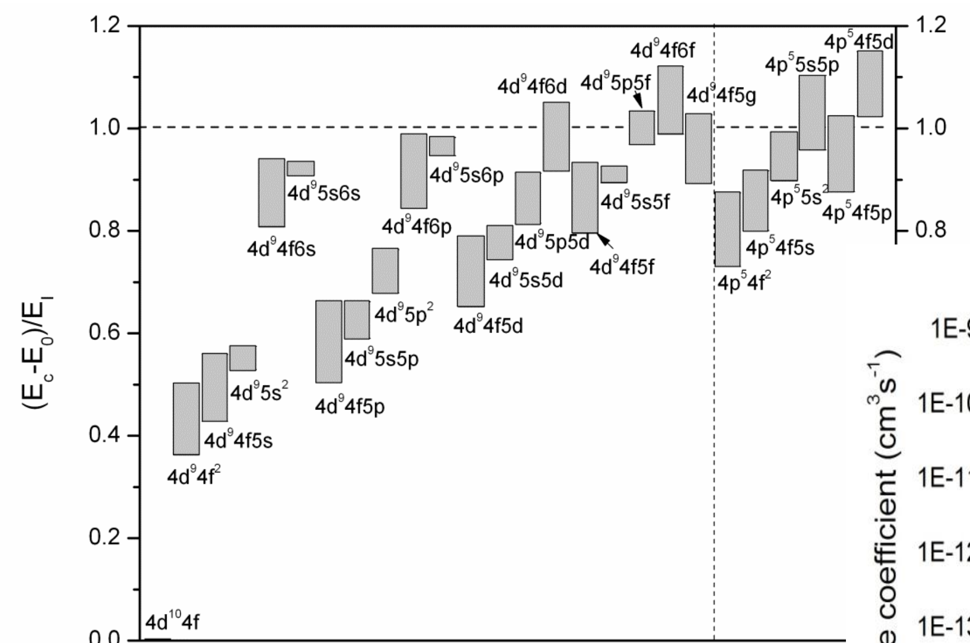
n_z = density of ion *z*,
n_e = electron density,
S = collisional ionisation rate coefficient,
α_r = radiative recombination rate coefficient,
$n_e \alpha_{3b}$ = three-body recombination rate coefficients and T_e = electron temperature

Problem: Dielectronic Recombination ignored

Time's arrow

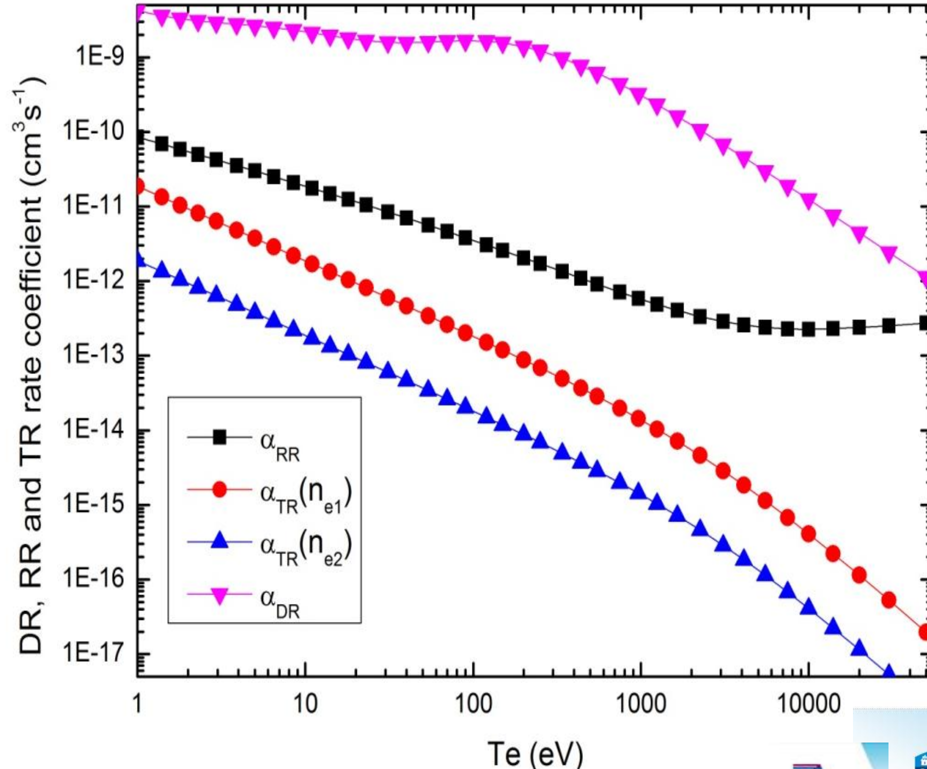


Dielectronic Recombination in Pd like Gd^{18+}



Energy levels of doubly excited configurations within the $4d^{10}4fnl$, $4d^{10}5snl$, $4p^54d^{10}4fnl$ and $4p^54d^{10}4fnl$ complexes relative to the first ionization limit.

Comparison of the DR, TR and RR rate coefficients for Pd-like Gd. The TR rate coefficients calculated for two electron densities, $n_{e1} = 10^{20}$ cm^{-3} and $n_{e2} = 10^{19}$ cm^{-3}



The Ground State Problem

PHYSICAL REVIEW A **82**, 062504 (2010)

Ground-state configurations and unresolved transition arrays in extreme ultraviolet spectra of lanthanide ions

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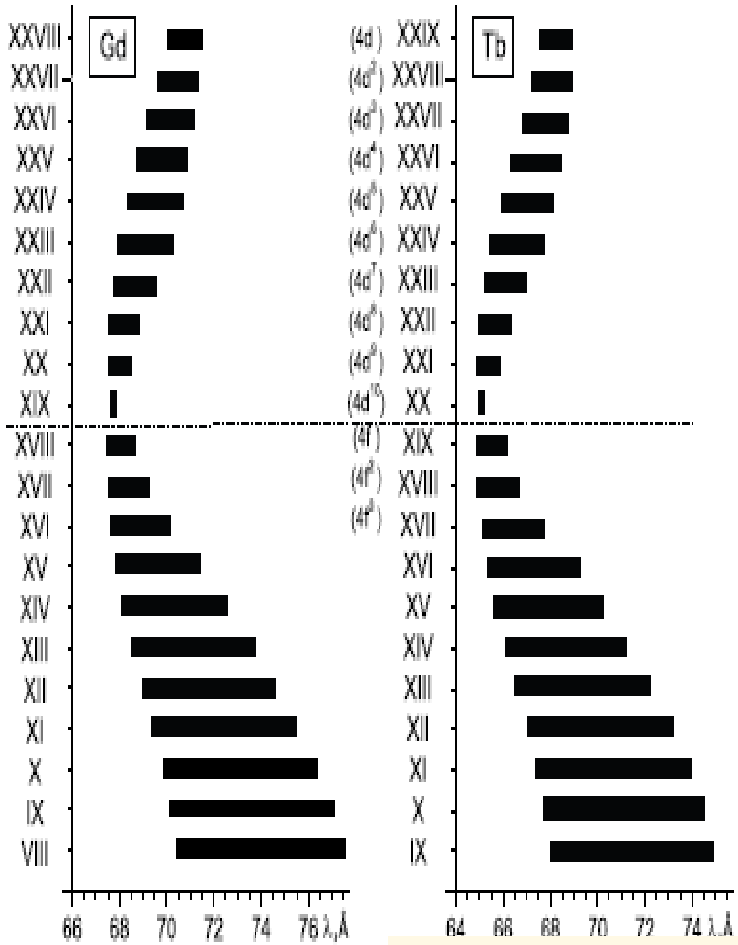
(Received 29 September 2010; published 6 December 2010)

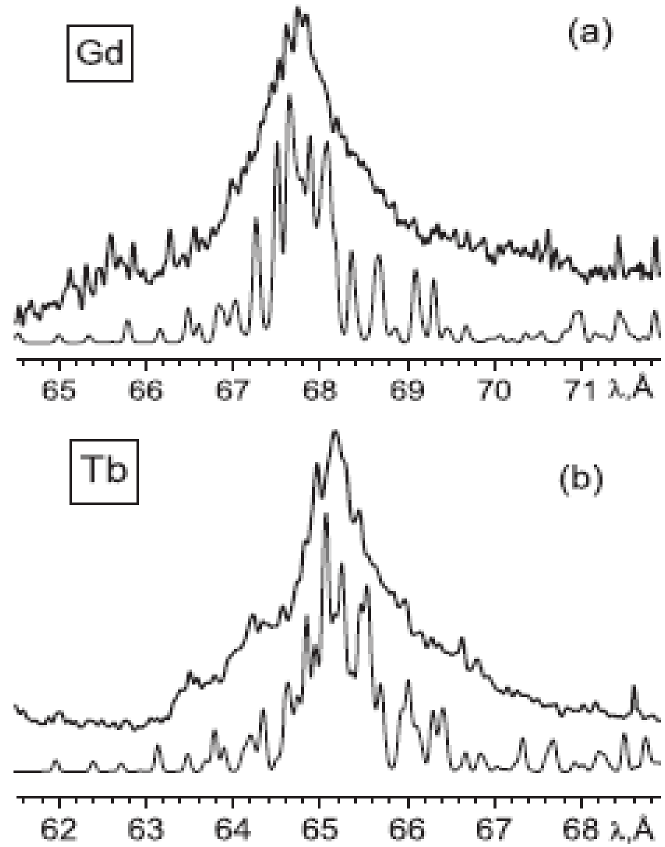
Theoretical ground-state configurations of lanthanide ions calculated with the Cowan suite of codes are presented. Theoretical $4d$-$4f$ and $4p$-$4d$ spectra of Pd-like to Rb-like lanthanide ions calculated using the relativistic flexible atomic code are also shown. The effects of configuration interaction are investigated, and the results compare favorably with experiments in which, for increasing nuclear charge, strong emission peaks are observed to move toward shorter wavelength. The application of these strong emitters as extreme ultraviolet radiation sources, a topic of emerging interest, is discussed.

TABLE II. Ground-state configurations of ions in stages V–XVII for elements lanthanum through hafnium. Discrepancies between the current table and Table I of [22] are highlighted in bold.

	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII
La	$5s^25p^5$	$5s^25p^4$	$5s^25p^3$	$5s^25p^2$	$5s^25p$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$	$4d^6$	$4d^5$
Ce	$5s^25p^6$	$5s^25p^5$	$\mathbf{5s^25p^4}$	$\mathbf{5s^25p^3}$	$\mathbf{5s^25p^2}$	$\mathbf{5s^25p}$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$	$4d^6$
Pr	$5p^64f$	$5s^25p^6$	$\mathbf{5s^25p^5}$	$\mathbf{5s^25p^4}$	$\mathbf{5s^25p^3}$	$\mathbf{5s^25p^2}$	$5s^24f$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$
Nd	$5p^64f^2$	$5p^64f$	$\mathbf{5s^25p^6}$	$\mathbf{5s^25p^5}$	$\mathbf{5p^34f}$	$\mathbf{5p^24f}$	$5s^24f^2$	$5s^24f$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$
Pm	$5p^64f^3$	$5p^64f^2$	$\mathbf{5p^64f}$	$\mathbf{5p^54f}$	$\mathbf{5p^34f^2}$	$\mathbf{5p^24f^2}$	$5s^24f^3$	$5s^24f^2$	$5s^24f$	$5s^2$	$4f$	$4d^{10}$	$4d^9$
Sm	$5p^64f^4$	$5p^64f^3$	$\mathbf{5p^64f^2}$	$\mathbf{5p^54f^2}$	$\mathbf{5p^34f^3}$	$\mathbf{5p^24f^3}$	$5s^24f^4$	$5s^24f^3$	$5s^24f^2$	$5s^24f$	$\mathbf{5s4f}$	$4f$	$4d^{10}$
Eu	$5p^64f^5$	$5p^64f^4$	$\mathbf{5p^64f^3}$	$\mathbf{5p^54f^3}$	$\mathbf{5p^34f^4}$	$\mathbf{5p^24f^4}$	$5s^24f^5$	$5s^24f^4$	$5s^24f^3$	$5s^24f^2$	$\mathbf{5s4f^2}$	$4f^2$	$4f$
Gd	$5p^64f^6$	$5p^64f^5$	$\mathbf{5p^64f^4}$	$\mathbf{5p^54f^4}$	$\mathbf{5p^44f^4}$	$\mathbf{5p^24f^5}$	$5s^24f^6$	$5s^24f^5$	$5s^24f^4$	$5s^24f^3$	$\mathbf{5s4f^3}$	$4f^3$	$4f^2$
Tb	$5p^64f^7$	$5p^64f^6$	$\mathbf{5p^64f^5}$	$\mathbf{5p^54f^5}$	$\mathbf{5p^44f^5}$	$\mathbf{5p^24f^6}$	$5s^24f^7$	$5s^24f^6$	$5s^24f^5$	$5s^24f^4$	$\mathbf{5s4f^4}$	$4f^4$	$4f^3$
Dy	$5p^64f^8$	$5p^64f^7$	$\mathbf{5p^64f^6}$	$\mathbf{5p^54f^6}$	$\mathbf{5p^44f^6}$	$\mathbf{5p^24f^7}$	$\mathbf{5p4f^7}$	$5s^24f^7$	$5s^24f^6$	$5s^24f^5$	$\mathbf{5s^24f^4}$	$4f^5$	$4f^4$
Ho	$5p^64f^9$	$5p^64f^8$	$\mathbf{5p^64f^7}$	$\mathbf{5p^54f^7}$	$\mathbf{5p^44f^7}$	$\mathbf{5p^24f^8}$	$\mathbf{5p4f^8}$	$5s^24f^8$	$5s^24f^7$	$5s^24f^6$	$\mathbf{5s^24f^5}$	$4f^6$	$4f^5$
Er	$5p^64f^{10}$	$5p^64f^9$	$\mathbf{5p^64f^8}$	$\mathbf{5p^54f^8}$	$\mathbf{5p^44f^8}$	$\mathbf{5p^24f^9}$	$\mathbf{5p4f^9}$	$5s^24f^9$	$5s^24f^8$	$5s^24f^7$	$\mathbf{5s^24f^6}$	$\mathbf{5s4f^6}$	$4f^6$
Tm	$5p^64f^{11}$	$5p^64f^{10}$	$\mathbf{5p^64f^9}$	$\mathbf{5p^64f^8}$	$\mathbf{5p^44f^9}$	$\mathbf{5p^24f^{10}}$	$\mathbf{5p4f^{10}}$	$5s^24f^{10}$	$5s^24f^9$	$5s^24f^8$	$\mathbf{5s^24f^7}$	$\mathbf{5s4f^7}$	$4f^7$
Yb	$5p^64f^{12}$	$5p^64f^{11}$	$\mathbf{5p^64f^{10}}$	$\mathbf{5p^64f^9}$	$\mathbf{5p^44f^{10}}$	$\mathbf{5p^34f^{10}}$	$\mathbf{5p4f^{11}}$	$5s^24f^{11}$	$5s^24f^{10}$	$5s^24f^9$	$\mathbf{5s^24f^8}$	$\mathbf{5s4f^8}$	$4f^8$
Lu	$5p^64f^{13}$	$5p^64f^{12}$	$\mathbf{5p^64f^{11}}$	$\mathbf{5p^64f^{10}}$	$\mathbf{5p^44f^{11}}$	$\mathbf{5p^34f^{11}}$	$\mathbf{5p4f^{12}}$	$5s^24f^{12}$	$5s^24f^{11}$	$5s^24f^{10}$	$\mathbf{5s^24f^9}$	$\mathbf{5s4f^9}$	$4f^9$

First Calculation of Spectral Emission





Churilov et al Phys Scr. 80, 045303, 2009

FAC Code Calculations for Gd

JOURNAL OF APPLIED PHYSICS **108**, 104905 (2010)

Extreme ultraviolet emission spectra of Gd and Tb ions

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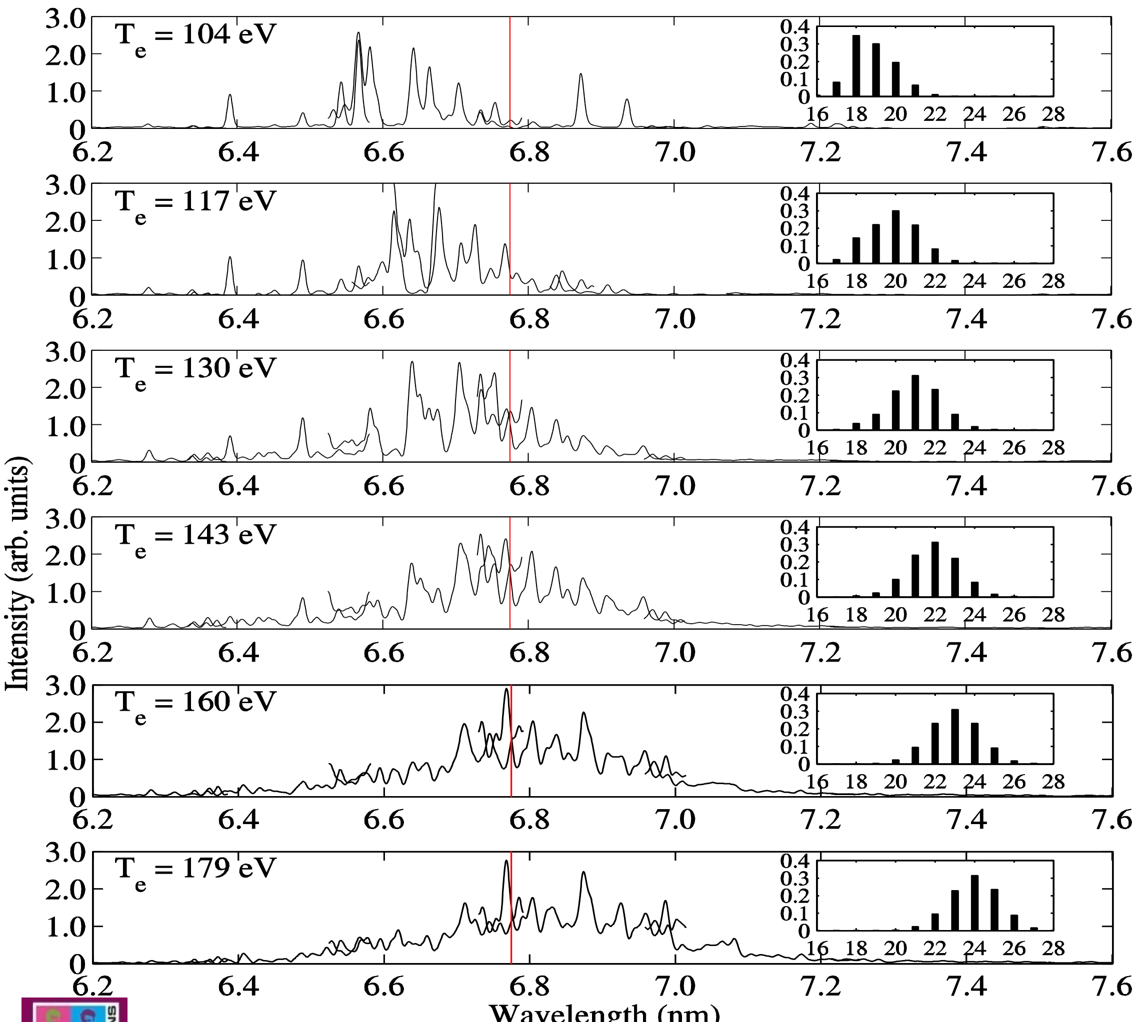
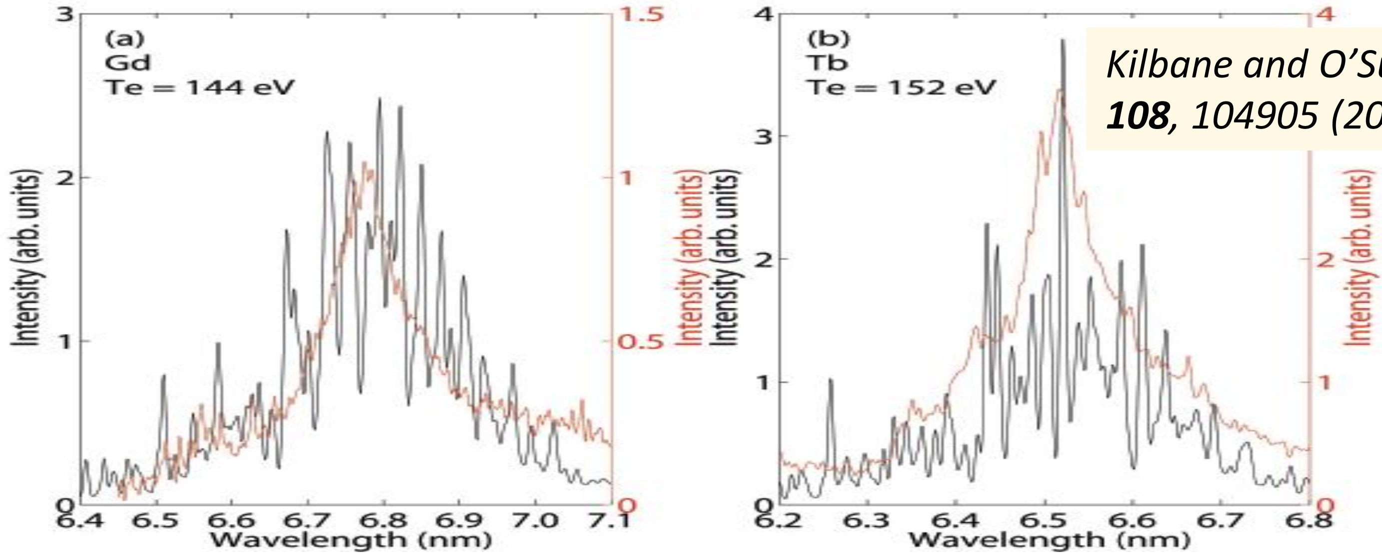


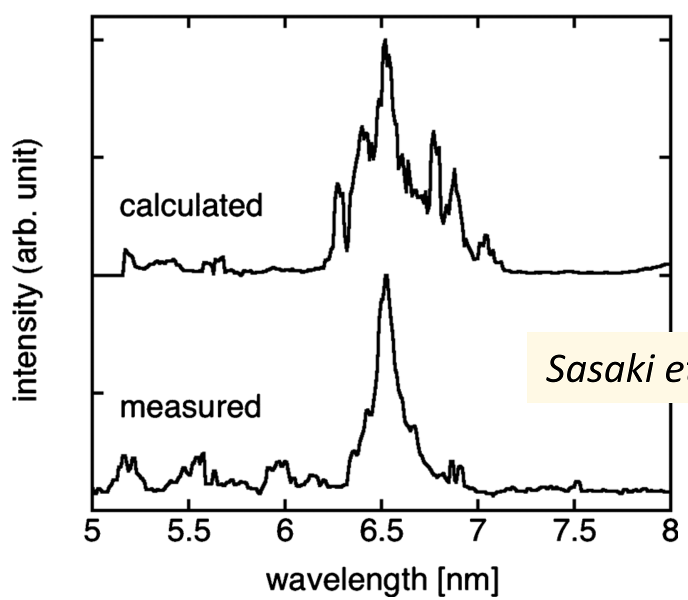
Calculations more complex than for Sn because of open 4f subshell in ions lower than 18+

In low stages, 4f, 5p and 4f, 5s level crossings give rise to very complex interacting configurations

Calculations for Gd and Tb spectra

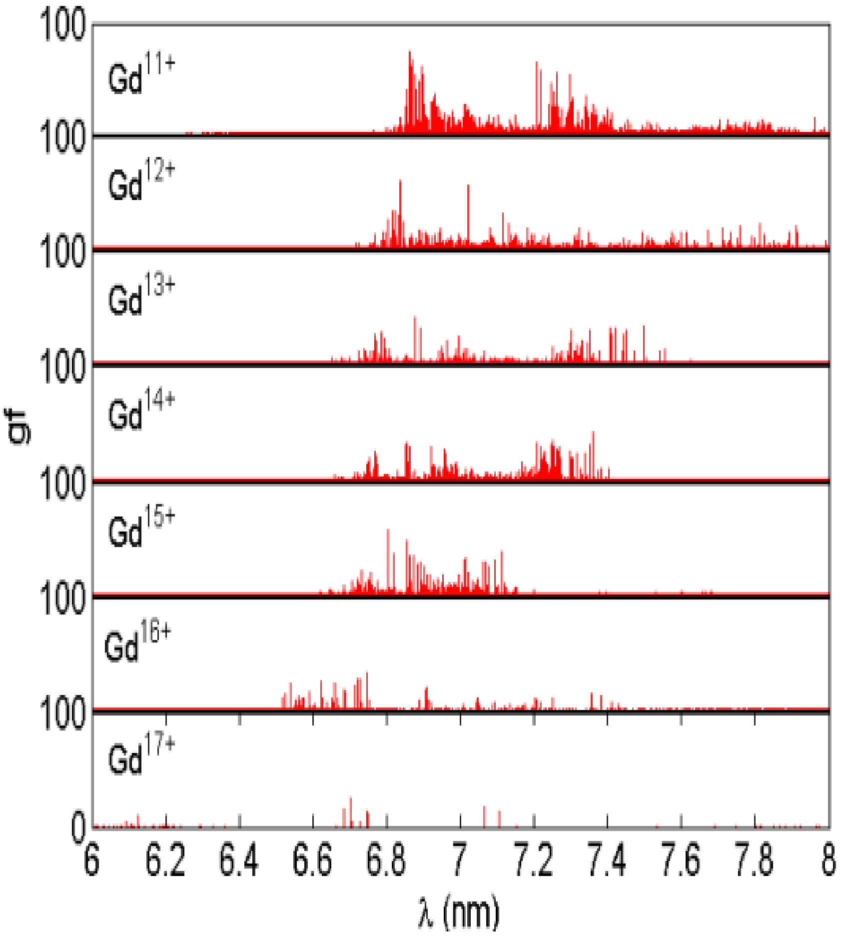


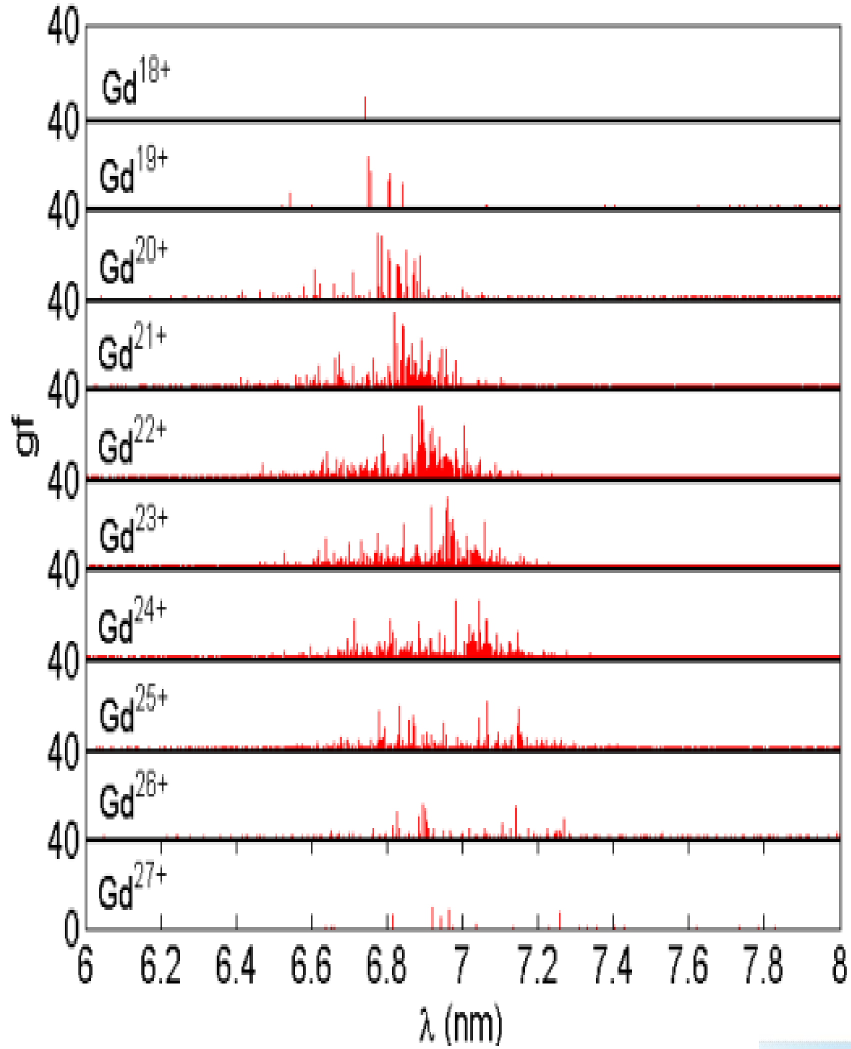
Kilbane and O'Sullivan JAP ***108****, 104905 (2010);*



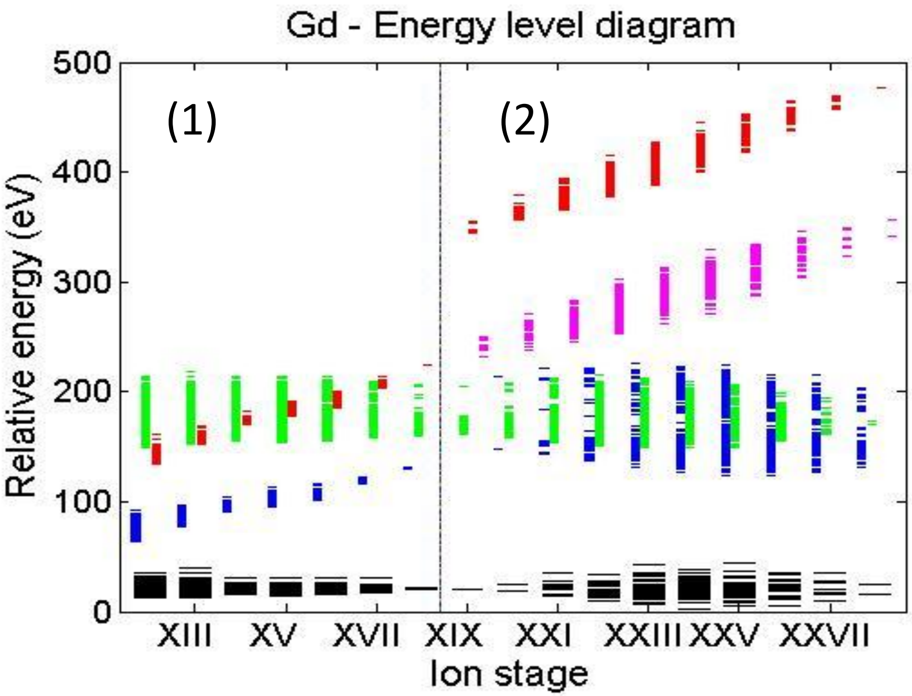
Sasaki et al APL ***97****, 231501 (2010);*

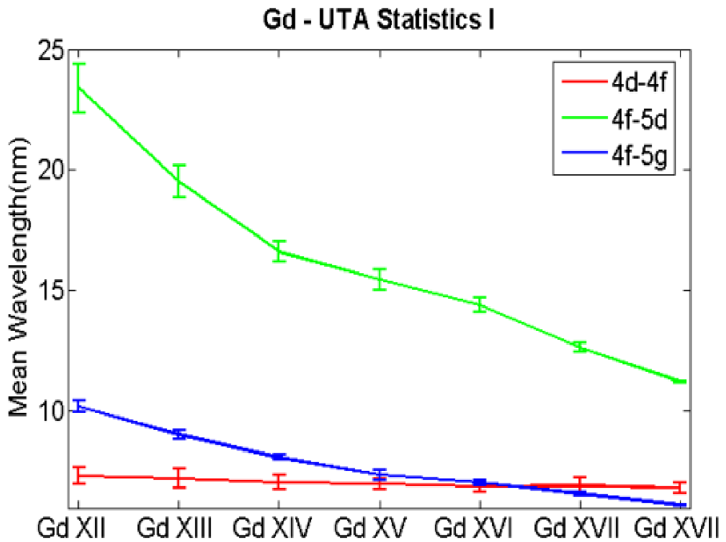
Cowan Code Calculations

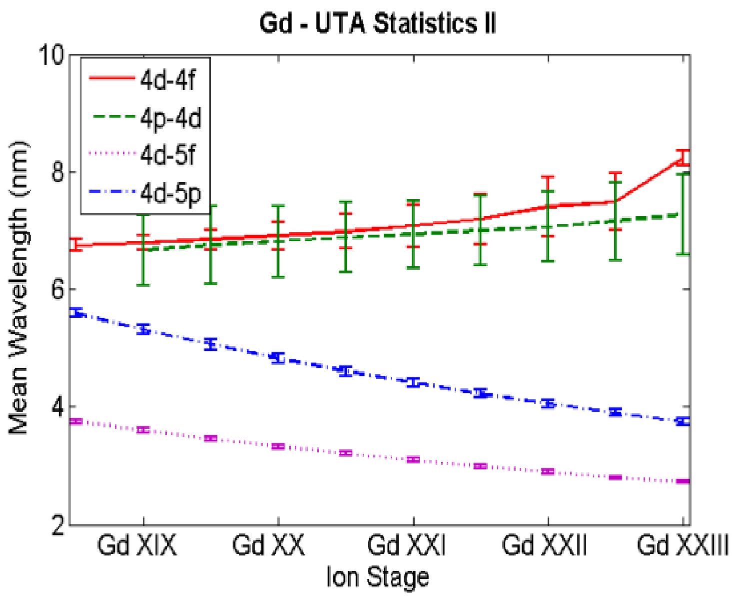




Levels and Transitions in Gd





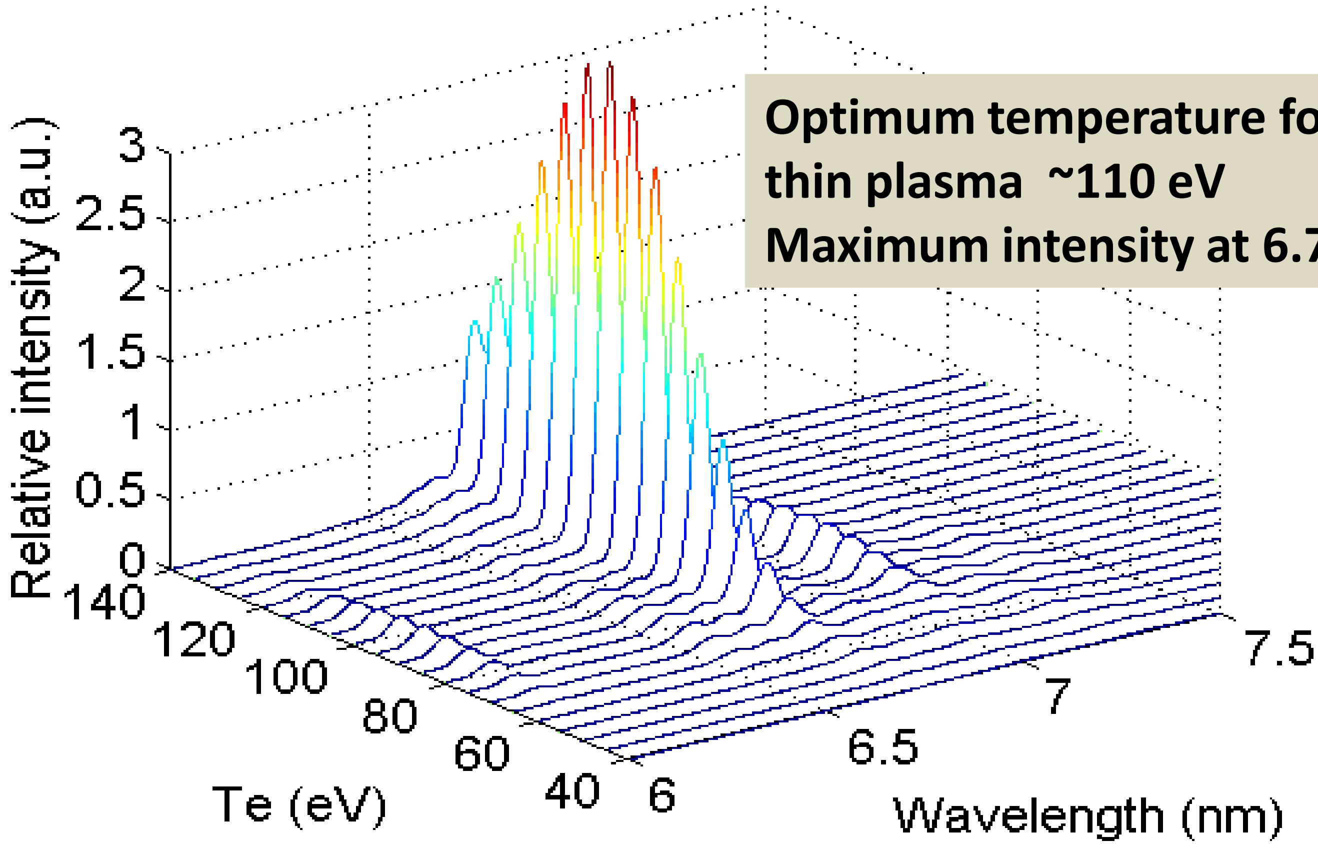


Energy-level diagram.

(1) Gd XII – Gd XVIII: 5d 4d^{-1} 5g and 4f.

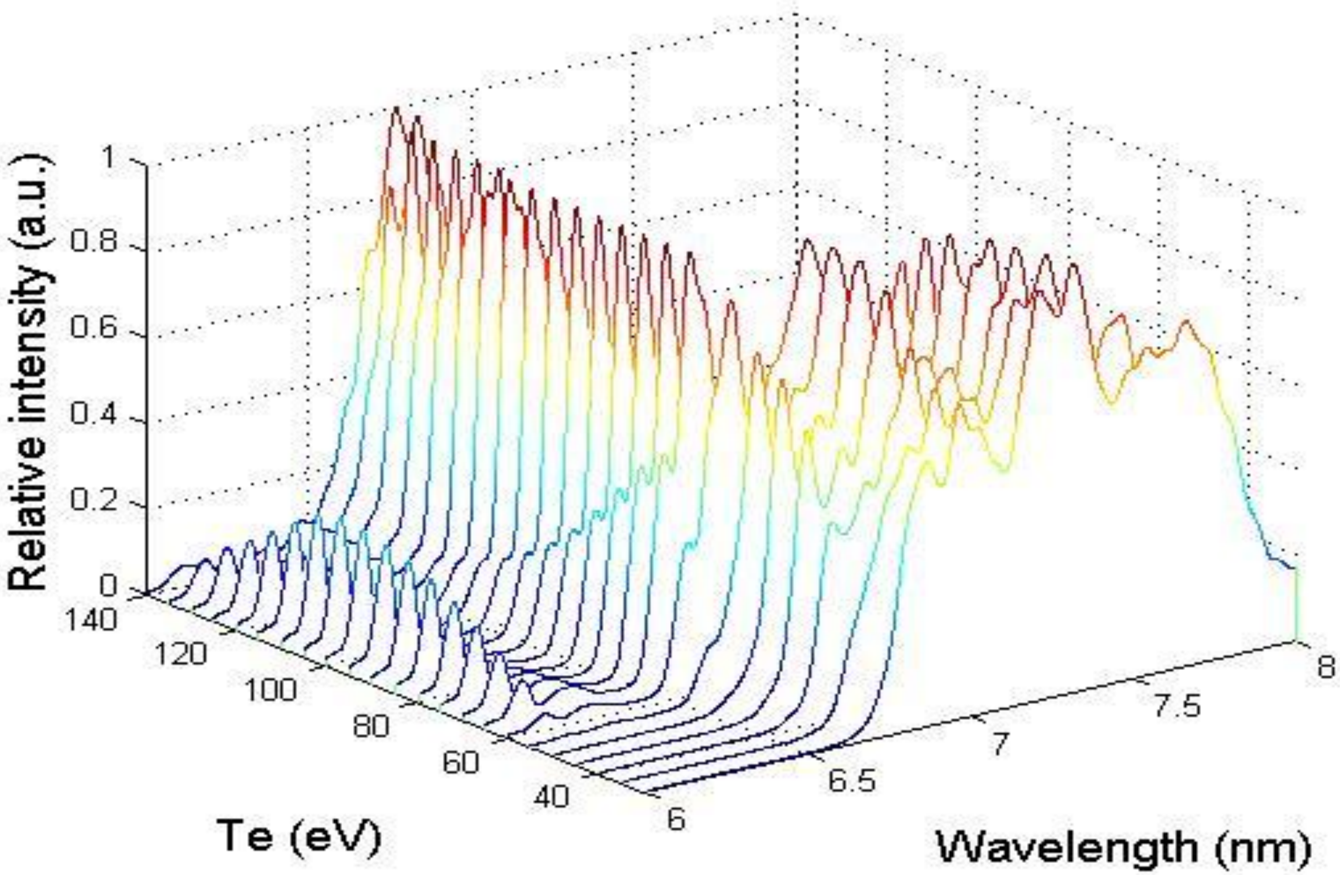
(2) Gd XIX – Gd XXVIII: 4p^{-1} 4f 5f 5p and 4d

Variation of UTA with Plasma Temperature (Gd)

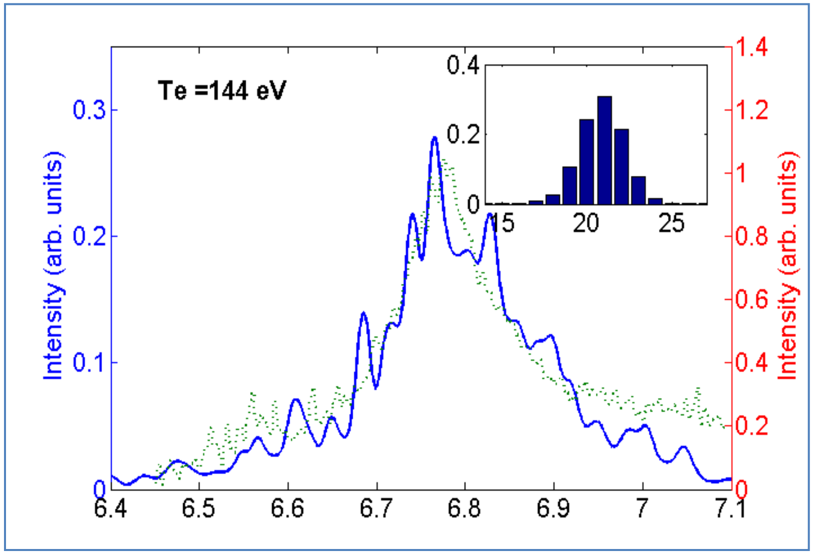


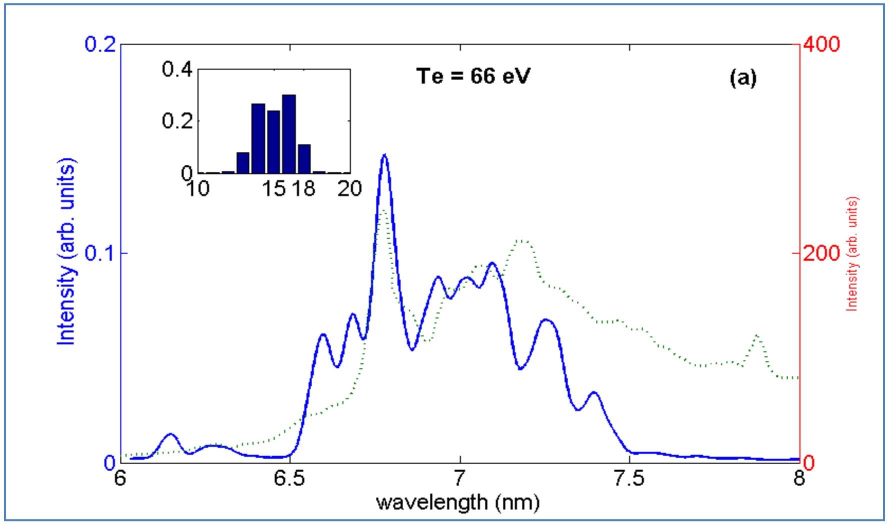
Optimum temperature for an optically thin plasma ~110 eV
Maximum intensity at 6.76 nm

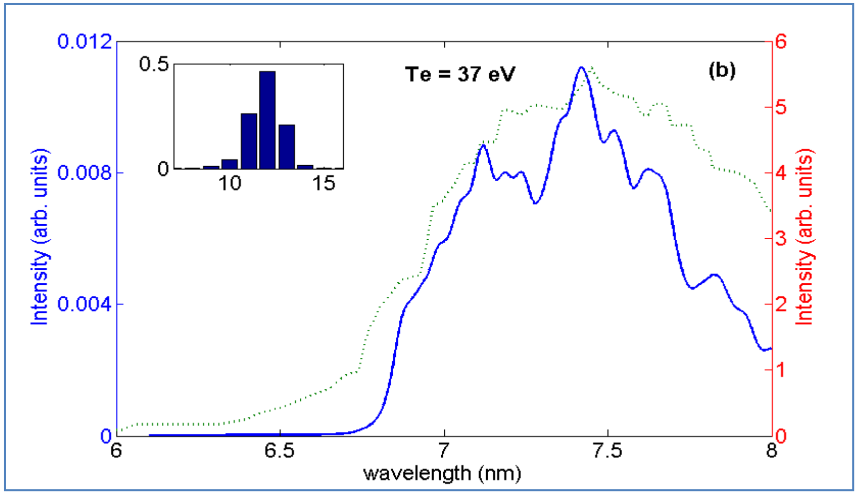
Spectral Profile Variation



Comparison with Experiment







Conclusions

6.X nm:

•Broadly same physics as Sn sources, ion stages with 4d subshell greater than half full now more important (opposite to Sn case)
•Complication due to ions with an open 4f valence subshell.
•Strongest lines expected from Ag-like and Pd-like ions **x=0.76 nm**
•T_e < 140 eV (~110 eV optimises 17+ - 19+)
•Opacity an issue…low density targets or CO_2 plasmas
•Ideally need short ~ 10 ns, flat-top CO_2 pulse
•$\Phi \sim 2\text{x}10^{11} – 10^{12}$ Wcm^{-2} @λ =10.6 μm
•CE will be lower because of higher plasma temperature

Thanks to

Collaborators:

- *Takako Kato, Daiji Kato & Chihiro Suzuki NIFS*
- *Hajime Tanuma, Tokyo Metropolitan University*
- *Dong Chenzhong & Su Maogen, Lanzhou*
- *K. Nishihara, H. Nishimura & S. Fujioka ILE Osaka*
- *A. Sunahara, ILT Osaka*
- *Fumihiro Koike, Kitsato University*
- *John Costello and Paddy Hayden, DCU*
- *Vivek Bakshi, EUV Litho Inc.*
- *Sergei Zakharov, Vasily Zakharov and Peter Choi, EPPRA*

UCD Group:

- *Emma Sokell, Fergal O'Reilly, Rebekah D'Arcy, Tom Mc Cormack, Ken Fahy, Paul Sheridan, Tony Donnelly, Larissa Juschkin, Niksa Krstulovic, Thomas Cummins, Brian Doohan, Colm Harte, Imam Kambali, Colm O'Gorman, Enda Scally, Robert Stefanuik, Frank McQuillan.*

Past Members:

- *Anthony Cummings, Paddy Hayden, John White, Nicola Murphy, Michael Lysaght, Gráinne Duffy and Ronan Faulkner.*

Acknowledgements

Science Foundation Ireland Principal Investigator Grant 07/IN1/I1771

EU Marie Curie IAPP Project FIRE

EU COST Action MP0601

Thank you